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FUEL CELL LOCOMOTIVES IN CANADA

D. S. Scott,* H.-H. Rogner* and M. B. Scott†

* Institute for Integrated Energy Systems, University of Victoria, P.O. Box 3055, Victoria, B.C., Canada V8W 3P6
† Scott and Associates Consultants Inc., 1601 Hollywood Place, Victoria, B.C., Canada V8S 1J6

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Abstract—Some railways and locomotive manufacturers have examined the prospect of deploying fuel cell locomotives over the next 15–30 years. This paper, growing out of such a study for Canadian National Rail, emphasizes tonnage trains, so important to Western Canada's economy.

The paper is founded upon the patterns in railway technological evolution set against the backdrop of world technological evolution. It reviews a matrix of technological pathways including: H_2 sources; onboard storage; range; duty cycles; and new train technologies like separate cabs and "smart trains." As to externalities to technological development, we only considered the prospect of legislation requiring that anthropogenic CO_2 emissions be incorporated in life-cycle costing.

Today, H_2 fuel cell locomotives miss feasibility by about one order of magnitude. If the capital cost and performance targets for fuel cells and ancillary technologies are met, H_2 fuel cell locomotives could break even with *improved* diesel locomotives in about 15 years. If the CO_2 externality is legislated into life-cycle costing, as is now being considered by several European countries, H_2 fuel cell locomotives may become the preferred option for rail motive power in North America.

1. PREMISES AND RATIONALE

1.1. *Introduction*

Most industrialized countries require a reliable, efficient and surprise-resilient railway system for a key portion of their transportation needs. This is particularly true in Canada, by area the second largest country in the world, where great distances between population centres and the need to transport bulk commodities make the railroad system essential to the current and future economic system.‡

Rail is important to the economy of all regions of Canada: wheat, potash, coal, sulphur and, to a lesser degree, lumber, have no option but rail. Moreover, for most of these commodities, Canada has the longest haul to tide water of any Western nation. For example, the mean distance to tide water for Canadian wheat is estimated to be 2000 km—compared with 650 km for the United States, 600 km for Brazil and 65 km for Australia. So, even small changes in the efficiency of rail transportation (measured, say, in $\$\,\mathrm{ton}^{-1}\,\mathrm{km}^{-1}$) have a profound effect on those industries that determine the economic strength of Canada. The impact f railway efficiency and reliability upon national economic health is, therefore, quantitatively larger in Canada than in most f the developed world. This is one of the reasons that evaluating generically new fuel cell locomotive technologies may be more critical to Canada's economic future than to most other nations. This paper analyses the cost, efficiency and technical constraints of fuel cell locomotives for development over the next two decades.

Before beginning the analysis of potential generic changes in rail motive power, we examined several questions about the future of railway services. First, we asked if any transportation system now emerging could supplant rail in transporting bulk commodities. We could identify no alternative transportation system likely to replace rail for these services.

Second, we asked if a generic locomotive change other than a fuel cell powered locomotive exists which has a prospect of widespread mainline deployment over the next 50 years. This study has been unable to identify any other realistic rail motive power system for long-distance deployment.

Finally, we enquired whether the existing locomotive fleet has the flexibility to begin changing the generic type of locomotive shortly after the turn of the century. The answer is yes. Locomotives have about a 30 year life span. In North America, diesel locomotives were introduced ver the two decades following World War II. Many of these are being replaced now, while locomotives introduced later will mostly be replaced by 2010.

Based on these answers, this paper examines the feasibility of fuel cell locomotive deployment during the early years of the 21st Century by these criteria: life-cycle costs, range, reliability, resilience to "surprise" and compatibility with other rail innovations like "smart train"

‡ This paper is drawn from a study performed for Canadian National Railways by Evenstar Energy Environment Economy Inc.

technologies. If the development of fuel cell locomotives is not feasible on these criteria, we do not expect that this technology will be "levered into feasibility" on the basis of commonly cited externalities such as fossil fuel depletion. In this paper, only CO_2 impact is included as an externality within the techno-economic envelope.

1.2. *Time horizon*

The recommendations in this paper are based on a 50 year time frame for two reasons:

Locomotive life cycles and fleet procurement timelines.
Innovation waves.

The following anecdote illustrates fleet locomotive life cycles.

In April, 1988, one of this paper's authors met with a Senior Vice-President of Canadian National Railways (CN) in an executive car behind Toronto's Union Station. The locomotive pulling the car into Union Station from Montreal that morning was a GP-9 purchased in 1956—32 years earlier. The procurement policy that led to the GP-9 being part of the CN fleet was formulated earlier still. Similarly, most railway procurement strategies of today will influence the shape of their fleet into the 2040s.

The second, and somewhat less tangible reason for a 50 year time horizon is that such a span appears to coincide with typical innovation waves and infrastructure development. Evidence for these waves has been given in studies conducted by the International Institute for Applied Systems Analysis (IIASA) [1] and elsewhere. The IIASA work suggests that innovations tend to group in 55 year waves and that, after commercial introduction, an innovation's market penetration seems to grow steadily, its growth only weakly dependent on external influences.

These macro-economic observations correlate well with 20th Century railway development. In North America, the last generic innovation in motive power—the replacement of steam by diesel engines—began in the 1940s. This timing corresponds with the last innovation wave identified by IIASA and coincides with a maturing oil age. According to the IIASA studies, the next innovation wave should therefore begin about 2000, coinciding with a maturing methane age. The 50 Year Anniversary issue of *Trains* (November, 1990) provides an excellent chronology of railway events, including the penetration of the diesel locomotive. Reviewing the "significant milestones" listed in that chronology, the 1940s are filled with innovations in locomotive motive power such as the diesel, diesel-electric, steam turbine and gas turbine trains [2]. As the chronology moves into the 1950s and 1960s, milestones show the steady replacement of steam power by diesel motive power (with the last steam locomotives disappearing by the end of the 1960s), an evolution apparently undiverted by wars, periods of economic boom or recession, or political actions.

However, beginning in the late 1960s and continuing through to the 1990s, the chronology of milestones changes in character and describes activities about people, n stalgic exhibits, or instituti nal adjustments like mergers and bankruptcies. Technical innovation no longer makes the news. Taken together, the IIASA innovation wave studies as well as *Trains*' "snapshot" of North American railway corporate emphasis over the last 50 years lead to the following statement:

> Because of the railway's continued importance to the economy, it is essential that railways participate fully in the next innovation wave. If the railways miss this innovation wave, it will almost certainly accelerate their declining share of the transportation market.

1.3. *Environmental considerations*

The growing public awareness of such issues as toxic waste, water pollution and acid rain requires consideration of the environment when calculating costs for present or future technologies. This is particularly true for one issue having global rather than regional ramifications: climatic instabilities caused by greenhouse gases.

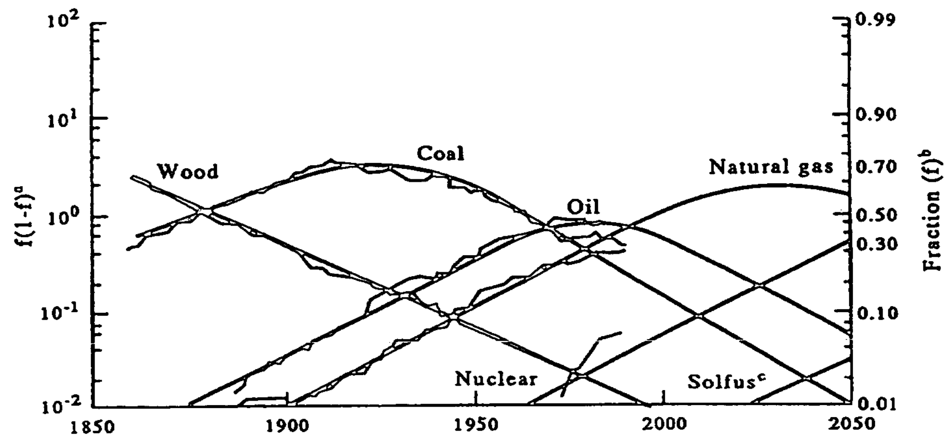
It is likely that over the next few decades, economic and human disasters will be attributed to anthropogenic climatic instabilities. Public fear of climatic change will grow, uncertainties about its impact will vanish and attacks on large energy users will develop and intensify. Prudent energy users should anticipate and prepare for these attacks. Preparation means developing strategies that will provide a measure of resilience to the political shocks emanating from climatic surprise—and may even provide opportunity from the same conditions.

It is also likely that over the next few decades, it will become evident that civilization is evolving towards an ultimate hydrogen age. In the deep future, this hydrogen age will be characterized by the pervasive use of the two energy currencies hydrogen and electricity, with little use of fossil fuels and their technologies so familiar today. The transition to this age will require about a century to complete. However, the first wave of this transition, the use of hydrogen as a chemical tether within integrated energy systems, has already begun [3]. In addition, the second wave—the use of hydrogen in the transportation sector—seems poised to expand from aerospace technologies, the forerunner of terrestrial applications.

While the greatest *single* threat to climatic stability is from CO_2 emissions from energy transactions, the growth in atmospheric CO_2 is not attributable solely to these emissions. Nevertheless, since they are the most tangible and quantifiable, CO_2 emissions from transportation could be the first to be regulated through legislation. Railways use only a small percentage of the petroleum-based fuels and move freight with a much lower CO_2 ton^{-1} km^{-1} emission than other forms of transport. Yet often legislation is "broad brush" and may affect railways as much as trucking.

1.4. *Energy and technology patterns*

The competition for market share among energy sources is depicted in Fig. 1. This well-known graph demonstrates how coal replaced wood as a primary fuel source. Oil then



[a] Market share of a technology or primary energy form divided by the market share not reached by this technology.
[b] f = market share.
[c] Solfus = solar and/or fusion.

Fig. 1. World primary energy substitution [1].

displaced coal and, today, natural gas is gaining an ever larger portion of the world's energy source market. A pattern in these fuel substitutions has been the replacement of low hydrogen/carbon (H/C) ratio fuels with progressively higher H/C ratio fuels: from wood with a 0.1 H/C ratio (when H_2O is removed) to coal with a H/C ratio of about 0.7–0.9 to natural gas with a H/C ratio approaching 4.

Hidden behind these patterns is that technologies, not fuels, compete in the market place.

Following World War II, diesel locomotives competed with steam locomotives to decide which would pull North America's trains. Diesel locomotives won. This was a competition between technologies, diesel locomotives against steam locomotives. It was not a competition between fuels, oil against coal, nor were we running out of coal. Yet the victor of the direct technological competition determined which fuel would be used. Oil won. Coal lost.

The winner in the competition between oil and coal was not decided by factors usually thought to determine head-to-head competition—factors like relative price or availability. Rather, it was determined by a competition to which these fuels were bystanders, a competition between technologies [3].

Technologies win because they are better. "Better" a deceptively simple word, is a more encompassing concept than, for example, "cheaper." Applied to light bulbs, in competition with coal oil lamps, "better" includes cleaner, safer, more convenient, brighter and ultimately (but not initially) cheaper. For diesel locomotives in comparison with steam, "better" once again means cleaner, but it also means longer distances between refuelling (and rewatering) and ultimately, cheaper. Similarly, the transition to a natural gas dominated age must also be seen in the c ntext of technologies that will be better—technologies providing special benefits by exploiting their use of natural gas, or natural gas derived fuels, of which hydrogen may become the most important.

Natural gas sourced fuels will almost certainly make a major entry into the transportation sector over the next three decades. Very likely, natural gas will, in part, enter transportation through hydrogen. Hydrogen derived from natural gas by steam-methane reforming (SMR)—today's most prevalent form of hydrogen production—is expected to provide a growing market for natural gas and an important platform from which to develop hydrogen technologies. Non-fossil derived hydrogen will win over SMR H_2 in site-specific circumstances when it can be produced at lower cost—or if CO_2 legislation requires it.

1.5. *How the fuel cell locomotive fits in with railway innovations*

Several innovations have recently been introduced by railways and are part of a trend to modernize rail support, increase efficiency and reduce costs. These include:

- The development of "*smart trains*" using computers to plan routes, perform onboard diagnostics for maintenance and inspect track while rolling. Hookups with a main computer provide continual information on the train's location, thereby improving safety significantly. It also allows for en route freight pickups or delivery.

Other developments planned which can be combined with the introduction of new motive power include:

- *Separate crew compartments* isolating the operator's cab, presently staffed by two people, from the motive power unit. This "leading pod" or control compartment significantly reduces noise in the control cab and

thereby improves personnel comfort.

- The fuel cell produces *d.c. electricity*, thus eliminating the need for the power rectification currently required by today's diesel electric units. Should future locomotives adopt *a.c. motors*, power controlling must still begin with d.c. current and so the fuel cell output remains preferred to today's alternator output.

Significantly, a change to fuel cell locomotives would not require serious infrastructure modifications. Fuel cell locomotives can operate on existing roadbeds and use existing fuelling facilities adapted to dispense hydrogen. Mature fuel cell locomotives will almost certainly allow longer intervals between maintenance and maintenance will form a lower fraction of the integrated operating costs.

2. TECHNO-ECONOMIC ANALYSIS

2.1. *Fuel cell background*

Fuel cells—not being heat engines—offer the possibility of highly efficient electricity production by the direct conversion of fuels into electricity. Yet until recently, except for some highly specialized applications primarily in aerospace, techno-economic performance profiles did not make this technology viable for commercial applications. Recent advances in fuel cell technology, however, have now markedly improved the prospects for fuel cell applications in several commercial settings. One of the most attractive of these settings is railway motive power.

Still, as with any new technology, fuel cell entry into the commercial market will meet fierce competition in two categories:

- Established technologies that will be endangered by the innovation.
- Differing system design approaches required by the new technology performance envelope.

In addition, educating customers on the techno-economic viability of the new technology always slows the initial pace of market penetration.

From the perspective of technology, the various generic fuel cells exhibit differences in their use of electrolyte and temperature of operation. Table 1 lists today's principal types of fuel cell and their main characteristics.

We believe that two of the fuel cells listed in Table 1 may be especially suitable for transport power generation, alkaline fuel cells (AFCs) and proton exchange membrane cells (often labelled solid polymer fuel cells or SPFCs), although other studies have examined phosphoric acid and even molten carbonate cells [4]. The ability of the AFC and SPFC to deliver power at ambient temperature is one reason why these types of fuel cells are attractive to the transport sector. We believe that most other types of fuel cells will be found to be restricted to stationary applications due to operating temperature, weight, ancillary equipment requirements, startup considerations and overall complexity.

Today, the SPFC type fuel cell may be the most promising technology to compete with the reference diesel fuelled locomotive power generator on the following grounds:

(1) Unlike AFCs, which require CO_2 scrubbed air or pure oxygen as an oxidant, SPFCs can operate on unscrubbed air.

(2) Presently, SPFCs appear to have gained a lead on AFCs for terrestrial transport applications, although this might result from the greater number of manufacturers concentrating on SPFCs rather than an inherent technical advantage.

(3) Several years ago, SPFCs were operated for 70,000 hours and, when shut down and dismantled for inspection (by General Electric), they showed no sign of deterioration. This is the longest operating life reported so far.

(4) SPFCs promise 1 MW per cubic metre (or 700 W kg^{-1}).

SPFCs still face technical and economic barriers which must be overcome for commercial success. These include:

(1) The need to step up from the kW to the MW range (this has been achieved by phosphoric acid fuel cells but not by SPFCs).

(2) The need to reduce capital costs per kW by at least one order of magnitude (there is no inherent reason why this goal cannot be achieved with mass production and is the stated target of fuel cell manufacturers).

(3) Continued performance improvement along the hydrogen delivery chain (in particular for onboard storage, where important breakthroughs such as magnetic liquefaction now look promising).

Table 1. Types of fuel cells [4]

Fuel cell type	Electrolyte	Operating temperature (°C)	Start up time (min)
Alkaline	Potassium hydroxide	50–90	5
Proton exchange membrane (solid polymer)	Polymeric	50–125	5
Phosphoric acid	Orthophosphoric acid	190–210	300
Molten carbonate	Lithium/potassium carbonate mix	630–650	500
Solid oxide	Stabilized zirconia	900–1000	100

2.2. *Fuel and fuel storage options*

2.2.1. *Methanol*. Today, mainstream trends appear to favour the use of alcohol fuels (for example ethanol, methanol and blends) as the first alternative to oil for most ground transportation applications. Methanol in particular seems guided by the desire of transport equipment manufacturers and policy makers to minimize interference with existing refuelling or onboard storage technologies and infrastructures. Of the alcohols, methanol is normally the first choice as a substitute for petroleum-based fuels in the transport sector's internal combustion engines.

Methanol is also often advocated for fuel cells, although it cannot be used directly, as it requires onboard reformation to hydrogen. Although such small-scale reforming of methanol is not an insurmountable impediment to fuel cell use, processes with fewer onboard conversion steps have historically proven superior.

2.2.2. *Hydrogen*. Rather than analysing onboard methanol as the feedstock for hydrogen, we believe that the direct use of hydrogen is more attractive as it eliminates the need for a reformer and simplifies control systems. We have therefore reviewed three options: hydrogen gas stored in metal hydrides, compressed gaseous hydrogen and LH_2. These hydrogen storage options must meet or exceed the volume and weight limitations/requirements, as well as the range, of a typical diesel locomotive. The present analysis uses a 15,600 l diesel fuel tank as the reference storage system and bases the locomotive range on the size of this fuel tank, yielding 1500–1800 km.

2.2.3. *Metal hydrides*. For reasons of safety, many people support the use of metal hydrides as a hydrogen storage medium. However, for locomotives, hydrides could also serve the need for traction ballast. This study therefore performed a preliminary analysis on FeTi as a low-temperature hydride representative and on MgNi as a high-temperature hydride.

FeTi desorbs hydrogen at temperatures below 80°C. Waste heat from the fuel cell system is sufficient to desorb the hydrogen. However, FeTi hydrides appear limited in other ways:

- The effective hydrogen payload in FeTi is currently about 1.5%, so 1 kg of hydrogen requires a hydride storage weight of 67 kg. To achieve the same energy capacity and range as the diesel, the FeTi hydride system weighs 215 metric tons or 25% more than the entire reference diesel locomotive (about 170 tons).
- Reducing the quantity of hydride to acceptable weight levels decreases the locomotive operating range to 30% of the diesel range to about 500 km.
- The present cost of hydride is about $20 kg^{-1} [5], translating to about $1 million for a range of 450–540 km.

For Mg-based hydrides, the hydrogen/storage weight ratio of hydrogen to hydride is around 7–8%. Thus, the total hydride storage weight ranges from 46 to 40 metric tons, a quantity just within today's locomotive weight limitations. However, the use f Mg-based hydrides in locomotives appears restricted in other ways:

- Mg-based hydrides desorb hydrogen at 250°C or higher, but these temperatures cannot be reached with the waste heat from any of the fuel cell systems we consider suitable for transportation. (Some people have proposed using molten carbonate fuel cells in locomotives, which would supply waste heat at temperatures suitable for these hydrides.)
- Part of the hydrogen fuel can be used to generate heat for desorption. The costs, however, are considerable: 25% of the hydrogen would be expended for heat production alone, almost eliminating the efficiency of the fuel cell over diesel generators and reducing the range.
- Increasing the hydride volume to make up for the heat production losses would increase the weight by about 25%. Present locomotive configurations pose a barrier to this tonnage.

Mixing high- and low-temperature hydrides might offer an opportunity for using the high heat generated by braking as a desorption mechanism (see Section 2.4). The drawback to this method is that the heat is generated for desorption when hydrogen is least needed.

2.2.4. *Compressed gaseous hydrogen*. Current pressure cylinders operate at a maximum pressure of 200 atm. To achieve the same energy capacity and range as the diesel, the volume and weight of the pressurized hydrogen storage system total 260 m^3 and 170 metric tons, respectively.

For compressed gaseous hydrogen to become a viable storage option would require cylinders operating at pressures of 600–700 atm. These ultra-high pressurized carbon-reinforced cylinders would reduce storage weight to 50–60 tons and the volume to 60–80 m^3. Present locomotive configurations pose a barrier to these dimensions. In addition, refuelling time at these pressures could exceed practicality.

2.2.5. *Liquid hydrogen*. Because of LH_2's high energy/weight ratio, weight limitations in fuel cell locomotives are not a consideration. In fact, if LH_2 is used, it may be necessary to add ballast to ensure sufficient traction. Metal hydrides could provide some of the ballast if appropriate duty cycle synergies were exploited.

When the higher efficiency of the hydrogen powered fuel cell is calculated, about 45,000 l of LH_2 provide the energy of a 15,600 l diesel engine. The weight of a cryofuel storage system including the payload hydrogen amounts to about 16,000 kg which corresponds closely to current diesel storage weight. Non-stationary cryofuel tanks have yet to be optimized and their weight is 2–4 times the weight of comparable stationary dewars. Optimization is likely to achieve substantial weight reduction.

The volume of LH_2 poses a constraint. In addition to the current 13 m^3 diesel tank, 34 m^3 of extra storage space is required. However, with the smaller size of the fuel cell assembly and imaginative design and engineering, enough space can most likely be created within the size of a standard locomotive.

When comparing LH_2 with either hydride storage or compressed gaseous hydrogen in fuel cell locomotives, LH_2 is the most effective way to maximize hydrogen energy storage on the basis of weight, range and cost.

2.3. *Techno-economic comparison of diesel vs fuel cell locomotive power generation*

The task of comparing a mature technology like the diesel generator to an embryonic technology like the fuel cell must be based on several assumptions and pre-analysis choices. These assumptions and choices clearly shape the analysis and may tilt the balance in favour or disfavour of the new—or old—technology. Hence, we wish to state these assumptions explicitly and to identify particularly those where small numerical variations strongly affect the results.

The following analyses are not forecasts. Rather, they represent techno-economic perspectives based on currently available information. These scenario analyses should be repeated as new information emerges. For now, sensitivity and "what if?" questions have been used to simulate different sets of data and assumptions.

This study has selected the Ballard SPFC as the "scratch" technology. If time proves other fuel cell technologies to be superior, then our analysis will have underestimated fuel cell locomotive prospects.

As to fuel choice, we have selected liquid hydrogen. Although the cost of liquefaction is high, LH_2 now appears to be the most viable option. Still, as with the SPFC, if LH_2 proves less desirable than another fuel, it is only because the other fuel is superior, and again, this analysis will have underestimated fuel cell locomotive prospects.

The reference points used in this study are the diesel-electricity power train and other specifications of the SD-60-II GM locomotive (at times complemented by data released to the SD-40-2 locomotive).

Current normal operating practice is to run freight trains on an irregular schedule, and often trains wait for a full load for a maximum of about 100 cars. The average trailing weight is about 5300 tons. Usually, one locomotive is allotted per 30 freight cars, so a normal train is pulled by three locomotives. Scheduled stops for freight trains are for crew changes and for refuelling; the range of locomotives is typically 1800 km.

The dimensions of present-day locomotives are unlikely to pose an impediment to fuel cell technology, as the fuel cell takes up less space than a diesel engine. We anticipate that fuel cell locomotives will be designed to carry about 45,000 l of LH_2 onboard using the extra space provided by the higher power/volume ratio of the fuel cell power plant.

The power per unit v lume ratio of fuel cells is about 5–7 times that of the diesel power plant (the power–weight ratio favours the fuel cell by a factor of 2). Onboard storage of LH_2 is thus an important feature; it does not necessarily require that the locomotive have a fuel tender and therefore opens locomotive duty cycles to short-distance hauls. Shunting and branch line delivery can also be easily accomplished.

We now turn to a comparative techno-economic evaluation of fuel cell vs diesel-electric locomotive power trains.

For diesel, the technology is mature and the fuel chain well established. Although the price of diesel fuel influences the economics of the diesel-electric locomotive, a detailed oil refinery and product distribution analysis would not create any new insights. Oil price levels are far more subject to international market turbulence and national energy policy than to future technical progress and innovation. Therefore, the analysis is restricted to the impact of diesel acquisition price variations on the locomotive's performance profile.

Therefore, our analysis focusses on the new fuel cell technology and the hydrogen delivery chain: fuel cell capital costs and onboard hydrogen delivery costs are the critical parameters.

The analysis of the hydrogen chain includes the following steps:

(1) Hydrogen production through steam-methane reforming. The principal energy input as well as the feedstock for the SMR process is natural gas (CH_4). The energetic output of this process is gaseous hydrogen (GH_2).

(2) Liquefaction of GH_2 into liquid hydrogen (LH_2).

(3) LH_2 intermediate storage and distribution.

(4) LH_2 onboard storage.

SMR was chosen as the principal hydrogen production process because:

(1) SMR is the most mature hydrogen production technology—more than 90% of present hydrogen production is based on this process.

(2) Natural gas is emerging as the world's leading primary energy source (see Fig. 1).

If site-specific or future circumstances allow water electrolysis to become less costly than SMR for the production of H_2, our analysis will again have underestimated fuel cell locomotive prospects.

2.3.1. *Comparison of future economics of hydrogen production and diesel costs.*

The techno-economic specifications of the SMR process, H_2 liquefaction and onboard storage are summarized in Table 2.

The analysis shows that liquefaction costs [5.9 \$(90) GJ^{-1}] approach SMR cost [6.0 \$(90) GJ^{-1}] in the hydrogen supply chain. Of course, once capital costs are established, both SMR H_2 production and liquefaction costs are determined by their respective feedstock/energy input costs.

Small variations in the cost of electricity [here priced at 0.045 \$(90) $(kWh)^{-1}$] can strongly impact on hydrogen supply costs. Similarly, the economies of liquefaction are very sensitive to small efficiency improvements in liquefaction technology. F r this study, we applied the large-scale, multistage refrigerati n process used by Union Carbide Corporation [6 and 7]. Present research forecasts that refrigeration efficiency will improve by 5–7% in the early 21st Century.

Larger efficiency gains, however, may be achieved by a novel liquefaction technol gy—magnetocaloric refrigeration. This technol gy may increase efficiency by 20–25%, as well as reduce investment costs. Everything else being

Table 2. Techno-economic specifications of the H_2 delivery chain. A real discount (or interest rate) of 10% per annum was applied. All cost data are given in Canadian dollars at 1990 prices and exchange rates. The cost calculations are based on technology life-cycle costs discounted by the real interest rate to the year 1990

System	Steam-methane reforming (GH_2)	Hydrogen liquefaction (LH_2)	LH_2 onboard storage†
Capacity (10^9 m^3 H_2 $year^{-1}$)	0.935	1.167	4.5×10^{-5}
Efficiency, η (%)	80	—	95–97
Lifetime (years)	20	20	20
Load factor (%)	90	90	70
CO_2 emissions (kg GJ^{-1} H_2)	65	0	0
Real interest rate (% $year^{-1}$)	10	10	10
Capital cost [\$(90) (1000 m^3 H_2)$^{-1}$]	113	150	61–32‡
O&M cost (% of capital)	7.7	5	2
Fuel (input) cost [\$(90) GJ^{-1}]	3.0	0.045*	—
Total cost [\$(90) GJ^{-1}]	6.01	5.91	1.75–0.97

*Electricity input in \$(90) kWh_e^{-1}.
†Actual onboard storage capacity.
‡In \$(90) m^{-3} of LH_2 capacity required to supply 1 kW of fuel cell capacity.

equal, this process could reduce liquefaction costs by about 1 \$(90) GJ^{-1}.

Once single-train units have reached an annual production capacity of 500×10^6 m^3, the SMR hydrogen production will no longer offer additional economies of scale. This study uses a pressure swing absorption SMR process with parallel trains based on an advanced design of polybeds from Union Carbide Corporation [8].

The price of natural gas directly affects hydrogen supply costs. We used 3 \$(90) GJ^{-1} for natural gas. Long-term production cost studies show that, once advances in geosciences and drilling technology are factored into the analyses, 3 \$(90) GJ^{-1} is a robust supply cost level [9]. Still, many factors, primarily of a political nature, may affect gas prices and, in spite of favourable perspectives, gas prices remain a critical parameter. Combined SMR technology and natural gas costs lead to hydrogen production costs of 6.0 \$(90) GJ^{-1}.

The remaining stages associated with the hydrogen supply chain are LH_2 distribution (including intermediate storage) and onboard storage. Distribution costs depend on many diverse factors. Most data are either very general or too site-specific for this study. Therefore, we assumed an average LH_2 distribution markup of 0.95 \$(90) GJ^{-1}.

The lower cost data for onboard storage given in Table 2 are based on the Linde Super Insulation cryogenic tank car (average evaporati n rate less than 0.5% per day beginning after 3–4 days f storage). These car tank data represent an achievable target when adapted for onboard locomotive storage by the year 2000. Current cost data are derived from a combination of medium-scale stationary dewars and vehicle hydrogen tanks. Capital costs include dewar, LH_2 pumps, venting equipment, coils, etc. The onboard LH_2 storage costs thus range from 0.97–1.75 \$(90) GJ^{-1} LH_2.

By this analysis, *the total cost of hydrogen delivered to the fuel cell locomotive is* 14.3 \$(90) GJ^{-1} today and 13.6 \$(90) GJ^{-1} for the year 2000; these figures serve as the reference LH_2 prices for the fuel cell locomotive performance analysis. The reference price for diesel was based on the latest available statistics of the average pre-tax price 0.24 \$(90) l^{-1} or 6.7 \$(90) GJ^{-1} to industrial consumers (1989 figures). From the perspective of resource availability and resource production costs, a price of 0.24 \$(90) l^{-1} is certainly a reasonable assumption for the medium-range future [9]. These price assumptions guard against the kind of surprises encountered in 1986 when oil prices plunged and investment projects based on increasing oil prices faltered.

2.3.2. *Locomotive power train specifications*. Table 3 summarizes the techno-economic specifications of the reference diesel-electric power train and the Ballard fuel cell technology. For the fuel cell technology, two time-dependent data sets for the years 1990 and 2000 were drawn up in collaboration with Ballard.

The most striking change during this period is the substantial lowering of the fuel cell's capital cost from about 6500 \$ kW^{-1} to a little below the 700 \$ kW^{-1} (Ballard's target is 250 \$ kW^{-1} and less). This reduction in capital costs reflects the anticipated positive impacts of the learning curve and the economies of scale. In high technology, cost reductions of a factor of 10 are more often the rule than the exception. In addition, an increase in fuel cell lifetime to 20 years by the year 2000 will be a nontrivial

accomplishment. The fuel cell technology must go through a decade of intense research and development as well as pilot and demonstration applications. As the turn of the century approaches, cost and performance profiles will be more accurate.

There will also be further technology improvements for mature diesel-electric power trains. However, these will be small in comparison with an embryonic technology like the fuel cell. Small variations in diesel capital costs may overshadow technology gains. Therefore, we did not consider technical improvements of the diesel-electric power train.

2.3.3. *Costs and efficiencies*. After analysing fuel costs, then technology development costs, we now examine onboard electricity costs and pathway energy efficiencies. The cutoff point for diesel-electric vs fuel cell comparison is just before the traction motor. After that stage, both systems are assumed to be identical. These are the results:

- The diesel-electric power train delivers electricity at 0.081 \$(90) kWh^{-1}.
- Fuel cell technology of 1990 results in a four-fold higher electricity cost than diesel-electric (0.334 \$(90) kWh^{-1}).
- Fuel cell technology in 2000 reaches production costs of 0.116 \$(90) kWh^{-1} (40% above diesel-electric). Fuel cell efficiency and capital cost reductions are chiefly responsible for this significant drop in delivered electricity costs.

The costs listed in Tables 2 and 3 represent a static situation. However, the cost calculations are sensitive to parameter variation. In particular, diesel, natural gas and electricity costs may alter the ranking of costs of onboard electricity production.

Figure 2 calculations depict the same technology parameters with varying diesel and natural gas prices. Natural gas and electricity do not appear directly in Fig. 2, but they determine the price of hydrogen and are therefore embedded within the cost of delivering electricity by fuel cells.

First we varied diesel prices between 0.2 and 0.5 \$(90) l^{-1}, while natural gas and electricity remained constant (see straight horizontal curve in Fig. 2). A 0.36 \$(90) l^{-1} (up by 0.12 \$(90) l^{-1} from the base price assumption) price for diesel makes the fuel cell technology of the year 2000 competitive, if fuel cell capital costs are reduced as stated in Table 3. Any further increase in diesel prices tilts the balance completely in favour of fuel cell electricity.

The second curve in Fig. 2 has natural gas prices trailing diesel prices. In this case diesel prices have to climb to 0.43 \$(90) l^{-1} before fuel cell electricity breaks even [while natural gas is priced at 5.37 \$(90) GJ^{-1}].

Because of the degree of uncertainty in today's knowledge about future technology performance, a look at the major cost components of fuel cell systems projected for the year 2000 may be helpful. Figure 3 depicts such a cost breakdown.

The larger the current cost estimates of a particular component, the higher will be the impact of even a small percentage improvement on overall fuel cell performance. This is especially true in liquefaction.

Natural gas pathways to nonstationary electricity generation, especially those involving hydrogen and fuel cells, are in the embryonic stage of their technical life cycle. Consequently, room for improvement as these technologies mature is significantly larger than for entrenched, mature systems. A small performance gap between a natural gas-hydrogen-fuel cell pathway and an optimized diesel system is a good indicator of potential success. In this

Table 3. Techno-economic specifications of locomotive power trains

System	Diesel-electric power train 1990	SPFC fuel cell cell stack and ancillaries 1990	2000
Power [kW (net)]	2862	6.9	22.4
Efficiency, η (%)	34	43	49
kW kg^{-1} power train	0.120	0.078	0.255
kW m^{-3} power train	11.8	76.7	248.9
Lifetime (years)	30	10	20
Load factor (%)	0.7	0.7	0.7
Fuel use (GJ km^{-1})	0.3872	0.3074	0.2672
CO_2 emissions (kg kWh_e^{-1})	0.76	0	0
Real interest rate (% $year^{-1}$)	10	10	10
Capital cost [\$(90) kW^{-1} (net)]	372	6457	696
O&M cost (% of capital)	5	4	3
Fuel (input) cost [\$(90) l^{-1}]	0.240	0.145	0.136
Fuel (input) cost in [\$(90) GJ^{-1}]	6.74	14.34	13.55
Fuel cost [\$(90) kWh_e^{-1}]	0.0714	0.1201	0.0995
Capital and O&M cost [\$(90) kWh_e^{-1}]	0.0095	0.2135	0.0167
Total cost [\$(90) kWh_e^{-1}]	0.0809	0.3336	0.1163

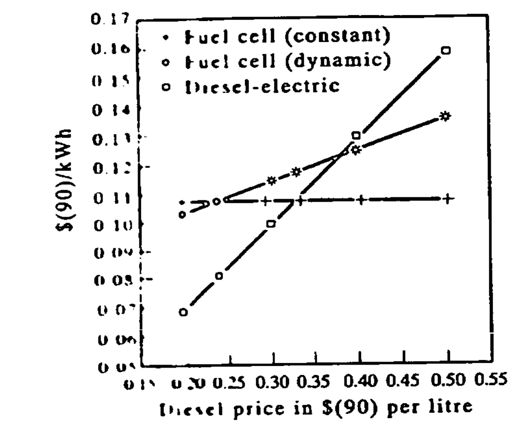


Fig. 2. Impact of diesel prices on fuel cell competitiveness.

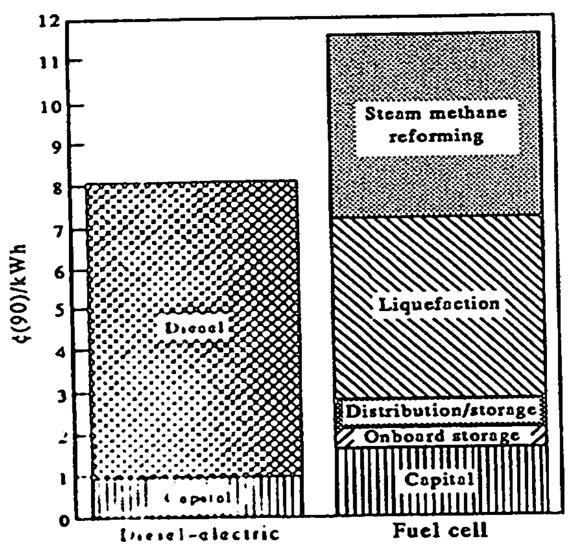


Fig. 3. Cost breakdown of locomotive power generation.

study, diesel electricity has a refining and delivery efficiency of [illegible]%, resulting in a pathway efficiency of 29%. Present fuel cell electricity has a pathway efficiency of 27% while by the year 2000, this efficiency increases to 31%.

These efficiencies must be used cautiously. The electricity needed for hydrogen liquefaction is non-fossil generated, reflecting Canadian electricity sources. If natural gas were used to generate electricity, these efficiencies would drop by 6%. For Canada, natural gas-hydrogen fuel cells are being fabricated and have a strong potential to exceed diesel pathway efficiencies by the year 2000.

Because the natural gas-hydrogen-fuel cell pathway technical gap is small, and technology development and optimization have yet to occur, we anticipate that improvements will first close the gap and then begin to outstrip diesel efficiencies. Economics will follow suit.

2.4. *Credit from regenerative braking*

Even across the large plains of central Canada, braking constitutes an important part of a freight train's duty cycle, and a relatively significant amount of kinetic energy is dissipated through heating. The amount of irrecoverable heat generated by braking is immense when tonnage trains traverse the western Canadian Rocky and Coastal Mountain ranges.

Present locomotive technology uses dynamic braking to control speed on descents or come to a complete stop. The principle of dynamic braking turns traction motors into generators. The electricity is dissipated into heating using toaster-like resistor grids placed on top of the locomotive. The heat is then dissipated to the atmosphere by a high-power air blower.

It is estimated that 25% of a train's duty cycle involves braking, and there is considerable interest in recovering this lost energy. In the European electrified rail system, dynamic braking simply feeds back electricity into the grid. This procedure is not possible in North America. One option proposed for capturing braking-generated electricity for a fuel cell locomotive is to develop a *reversible* fuel cell and convert the electricity into hydrogen. In such a configuration, the fuel cell would operate as an electrolysis unit. The resulting H_2 could be stored in metal hydrides serving as the traction ballast. To capture the full efficiency of regenerative braking electrolysis, the oxygen by-product should also be retained.

Although the concept of onboard hydrogen production is intriguing, from today's perspective, several factors appear to make this option unlikely:

(1) The design of a two-way operating fuel cell is likely to compromise fuel cell efficiency. A 25% share of braking in the locomotive duty cycle requires the benefits from regenerative braking to be 3 times larger than the losses of fuel cell efficiency.

(2) The option of installing a separate electrolysis unit appears technically feasible, but requires a large unit to be able to take advantage of peak braking power. In addition, the unit can only be used for 25% of the duty cycle, and sits idle when no braking occurs.

(3) The fuel produced by electrolysis is GH_2 which must be stored. Metal hydrides may be feasible, but compressed gas or liquefied storage make the economics look even less favourable.

(4) Our analysis shows a price range of 20–21 \$(90) GJ^{-1} for onboard compressed hydrogen production and storage costs, while the analysis shows liquid hydrogen can be acquired at less than 15 \$(90) GJ^{-1}.

N detailed estimates of potentially recoverable hydrogen from regenerative braking should be made until the prospects for less expensive electrolysis technologies improve. Capital reductions in fuel cell development are likely to reduce the electrolysis costs. Once these costs are

lower, costs of hydrogen production from regenerative braking should be recalculated.

An alternative route to utilizing dynamic braking is to compress air. SPFC technology will be likely to need compressed air as an oxidant. The fuel cell must provide the power to run the compressors. Air compression is thus a parasitic drain on fuel cell electricity production. The regenerative braking may substitute its compressed air, thereby improving the performance of the fuel cell power train.

2.5. *The impact of emissions*

The combustion products of fossil fuels are threatening the stability of the Earth's climate. Although the eventual socio-economic impacts of global climatic change are impossible to project, they will likely reach unprecedented magnitudes.

Far-sighted action requires the initiation of energy strategies that do not use the atmosphere for fossil fuel waste disposal. One early policy measure, particularly advanced in Europe, is to provide economic incentives to displace CO_2 intensive energy processes through carbon emission taxation.

Although no policy has yet been put in place, emission tax rates have been publicly debated. At the Paris based International Energy Agency, a 50 US$ tax per ton of coal equivalent (tce) was discussed in the spring of 1990. The Swedish Government in internal discussions toyed with CO_2 taxes as high as 110 US$ tce^{-1}. In costs per kilogramme of CO_2 emitted, these numbers translate into 0.023–0.05 $(90).

The enforcement of emission taxes applies the "polluter pays" principle and leads to the internalization of so far externalized costs. How would the internalization of the CO_2 emissions influence the fuel cell vs diesel-electric locomotive competition?

As described in Table 3, the diesel-electric locomotive power train produces 0.76 kg CO_2 per kWh_e of onboard generated electricity. Fuel cell operation has no CO_2 emissions. The imposition of CO_2 taxes of the order of 0.023–0.05 $(90) kg^{-1} would raise electricity costs by 0.017–0.038 $(90) kWh_e^{-1}. The full electricity production costs of the diesel-electric train would amount to 0.098 and 0.119 $(90) kWh_e^{-1} respectively. Fuel cell generated electricity costs remain unchanged at 0.116 (90)kWh_e^{-1}$.

At face value, the emission tax represents a comparative advantage for fuel cell generated electricity at the point of production. However, this advantage does not take all factors into consideration, since the hydrogen delivery chain is not free of CO_2 emission. The SMR process produces 65 kg CO_2 per gigajoule of hydrogen output. However, unlike the CO_2 emissions associated with the diesel-electric power train, SMR-produced CO_2 can be contained within the process and disposed of in an environmentally acceptable way. If however, the electricity needed for liquefaction is generated from the present production mix, we must add a carbon cost of 0.53–1.2 $(90) kWh_e^{-1} to the fuel cell generated electricity cost of 0.116 $(90) kWh_e^{-1}.

In summary, this brief analysis of CO_2 emissions and their impact on electricity production costs exemplifies the sensitivity of current transport systems to potential internalization of previously external costs. A least-regret-cost strategy—a strategy minimizing penalty costs in the case of most unfavourable events—should include early precautions against potential emission taxation.

3. CONCLUSION

Railways will very likely continue to be a major part of the transportation sector in North America throughout the next century. In part, this is predicted on the extraordinary long-term value of the established right-of-ways. The railways' share of the total freight transportation market is less certain, as are the categories of freight which trains will carry.

Any new technology attempting to enter the captive railway motive power market faces fierce competition from mature, optimized and well-established locomotives. In addition, the general infrastructure supporting diesel locomotives is effectively operating on a marginal cost basis. To overcome such market entry barriers, the new entrant must offer either significantly better economics, a substantially improved technical performance profile, significant environmental benefits, or all three. The latter includes the quality of transport services, the ultimate criterion for market success or failure. For freight transport, this means providing the fastest, safest, most reliable and least costly transport service.

Typically, initial costs handicap new market entrants, especially when a fundamental or generic technical change is introduced. Based on economics alone, sail would never have given way to steam for ocean transport. The significance of being "better" cannot be overemphasized.

As the 20th Century draws to a close, railways are approaching a critical decision point:

- Undertake enormous effort to reverse the long-term decline in their transportation market share.
- Face further decline and end up with merely the low-value bulk transport market.

To avoid the latter fate, railways must not only reshape management, marketing and services, but must also adopt the best technologies available. Because of the long lifespan of locomotives, strategic motive power procurement must include more than the simple business-as-usual approach. It demands long-term innovation assessment, based on an understanding of potential performance improvements of technologies at the beginning of their life cycles.

This paper has investigated the relative techno-economic position of an embryonic technology—the fuel cell—with respect to the established and mature diesel engine. At first view, the performance of the fuel cell appears uncompetitive. Costs are 4 times higher than for the diesel pathway. These high costs are caused primarily by the bench assembly of fuel cells and, to a lesser extent, the low efficiency of contemporary hydrogen liquefaction.

For pathway efficiency, the technical gap is much narrower. Despite the inefficiency of liquefaction, present fuel cell technol gy is at 27% efficiency and needs less than 10% improvement to cl se the gap with the diesel's effi-

ciency of 29%. Our analysis shows that, because the fuel cell technology is in the very early stage of its life cycle, the efficiency gap with diesel locomotives will close before the turn of the century and is expected to reach 31% efficiency by 2000.

Considering economics, costs can be reduced drastically by automated fuel cell manufacturing instead of lab assembly. Yet even automated manufacturing, combined with improvements in liquefaction efficiency and lower capital costs for LH_2 dewars, still leaves a cost gap of 40%, a substantial economic disadvantage for the fuel cell.

Environmental concerns, however, may force future economic accounting practices to include costs not borne today by the polluter. In that case, the 40% cost advantage of diesel may disappear instantaneously.

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